TFAWS 2025 Cryogenics Technical Session

Preliminary CFD Simulations of a Cryogenic Film Condensation Experiment

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THERMAL & FLUIDS
ANALYSIS WORKSHOP
Ames Research Center 2025

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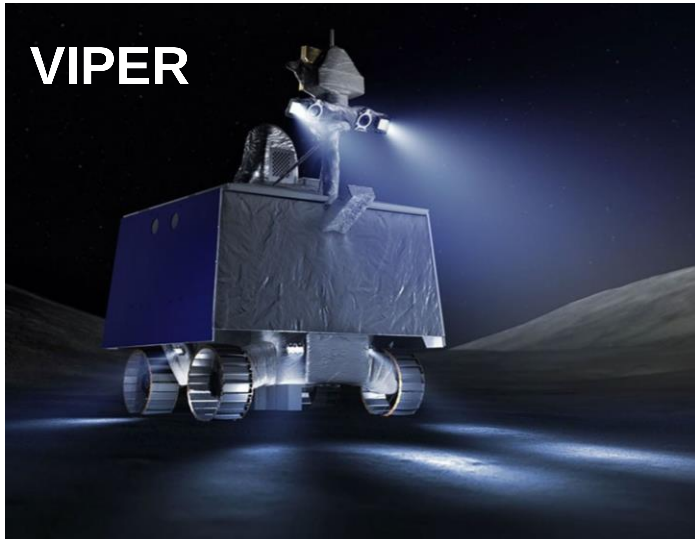
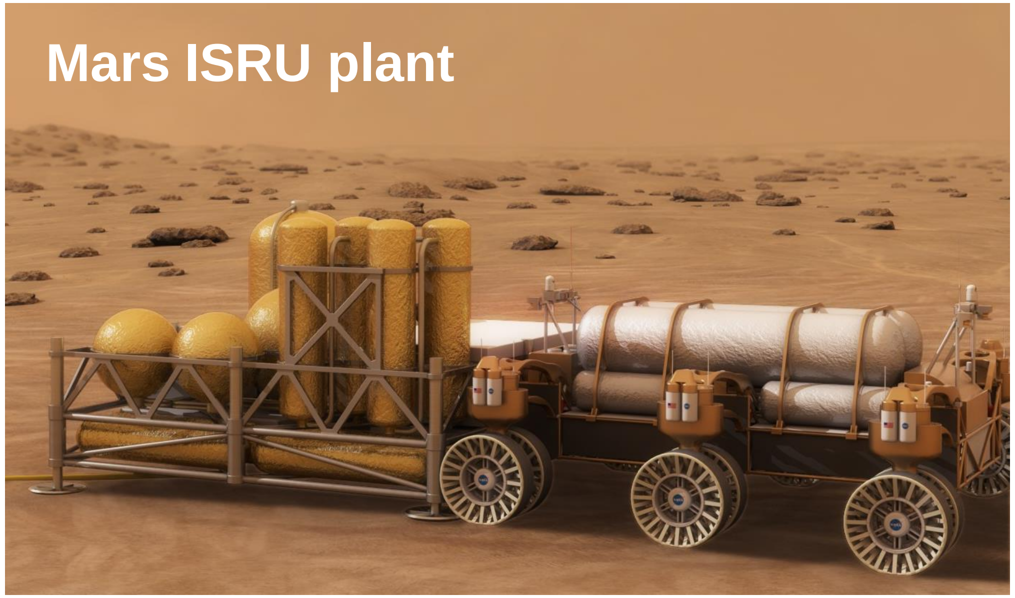
Outline

- Motivation
- CFM Model Validation Roadmap
- Film Condensation Experiment
- STAR-CCM+ Fluid Film Model with Phase Change
- Preliminary CFD Results
- References

Motivation

- In-Situ Resource Utilization (ISRU) is an enabling technology to maintain a sustainable presence on the Lunar and Martian surfaces
- ISRU plants will require liquefaction technologies to accumulate cryogenic propellants for ascent vehicles (LOX, LCH4)
- Liquefaction involves injecting gaseous propellant into a tank with active cooling to promote condensation
- CFD models can be utilized to predict liquefaction rates of cryogens at various operating conditions to determine:
  - Required duration
  - Power requirements
  - System efficiencies





Credit: NASA [1-2]

CFD Model Validation Roadmap

- Fundamental Film Condensation Experiment
- Cryogenic Fluid In-situ Liquefaction for Landers (CryoFILL)
  - Brassboard and Prototype testing
  - Nitrogen used as surrogate for Oxygen in Brassboard testing
  - Oxygen liquefaction for Prototype testing
  - Broad Area Cooling Neon loop

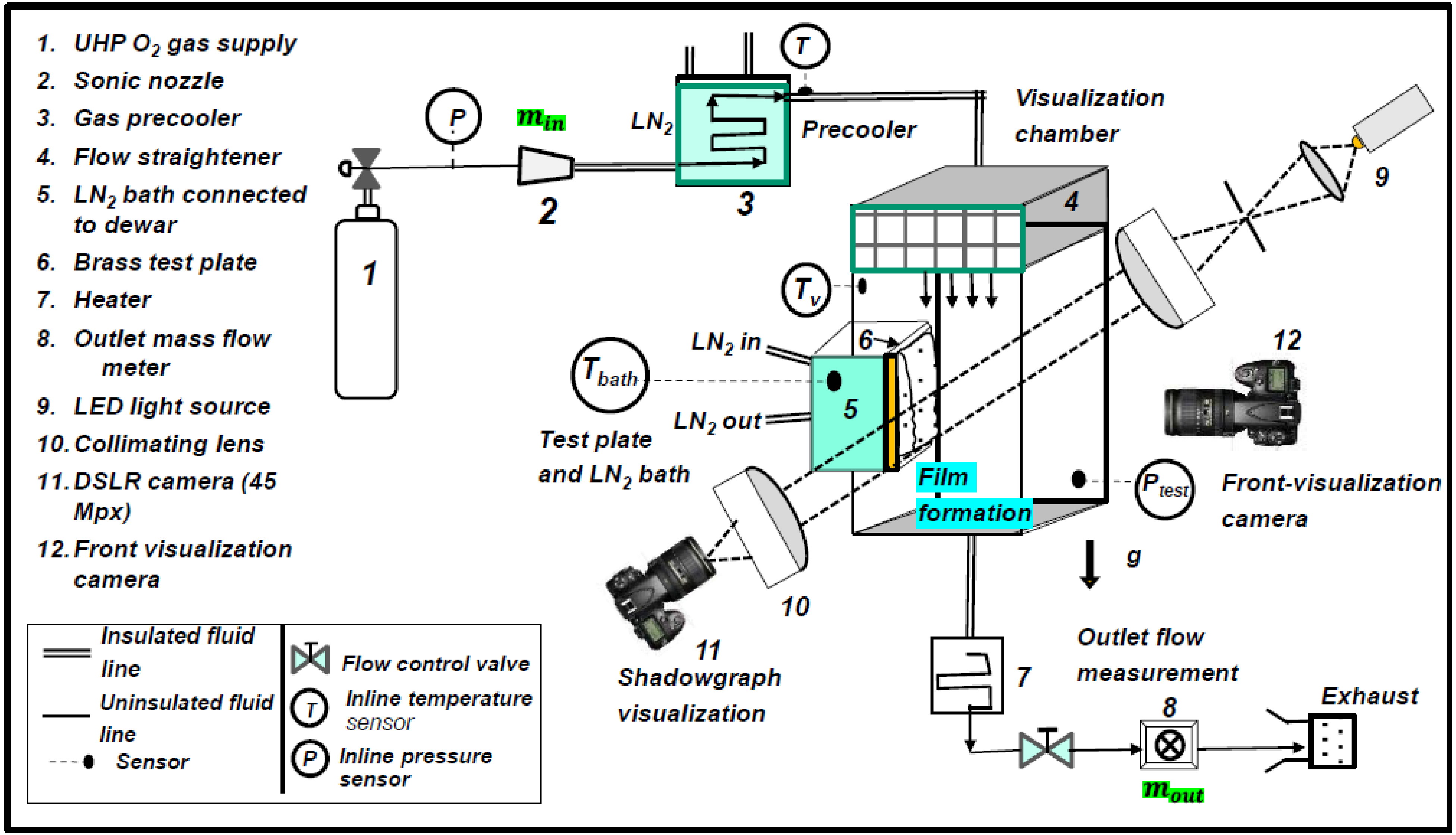
CryoFILL Prototype Tank

Ref [3]: Johnson et al., "Liquefaction of Cryogenic Fluids for Production and Storage of Commodities on Extra-Terrestrial Surfaces," Space Cryogenics Workshop, 2021.

Film Condensation Experiment: Overview

- Combustion Research and Flow Technology Inc. (CRAFT Tech) and University of Connecticut (UCONN) have completed two separate Phase I SBIR contracts on Film Condensation experimentation and modeling
  - July 2022 – Jan 2023 (80NSSC22PA988)
  - Aug 2024 – Feb 2025 (80NSSC24PB292)
- Phase II has been awarded for the most recent Phase I contract
- **SBIR Modeling Objectives:**
  - **Develop accurate sub-grid CFD models for modeling condensation of cryogens**
  - **Modeling framework shall capture growth and transport of liquid condensate while conserving mass, momentum, and energy**
- **SBIR Experimental Objectives:**
  - **Conduct fundamental film condensation experiments on a flat plate using Methane, Oxygen, and Nitrogen**
  - **Obtain measurements of pressure, temperature, flow rate, and film thickness (optical)**

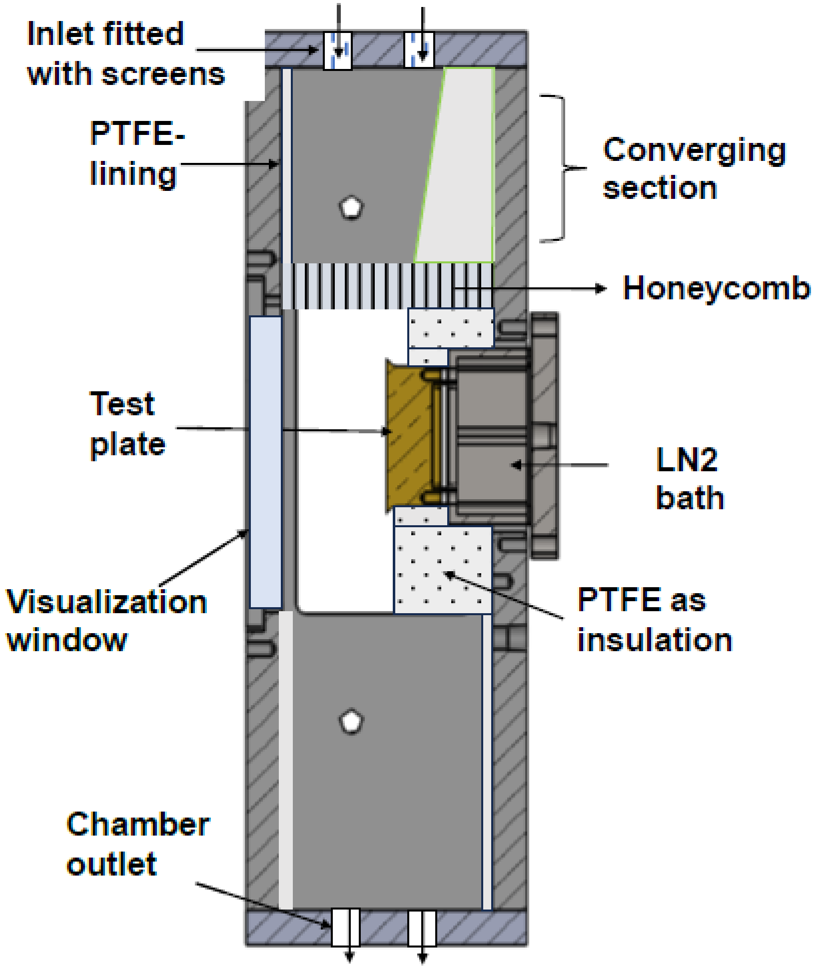
Film Condensation Experiment: Schematic



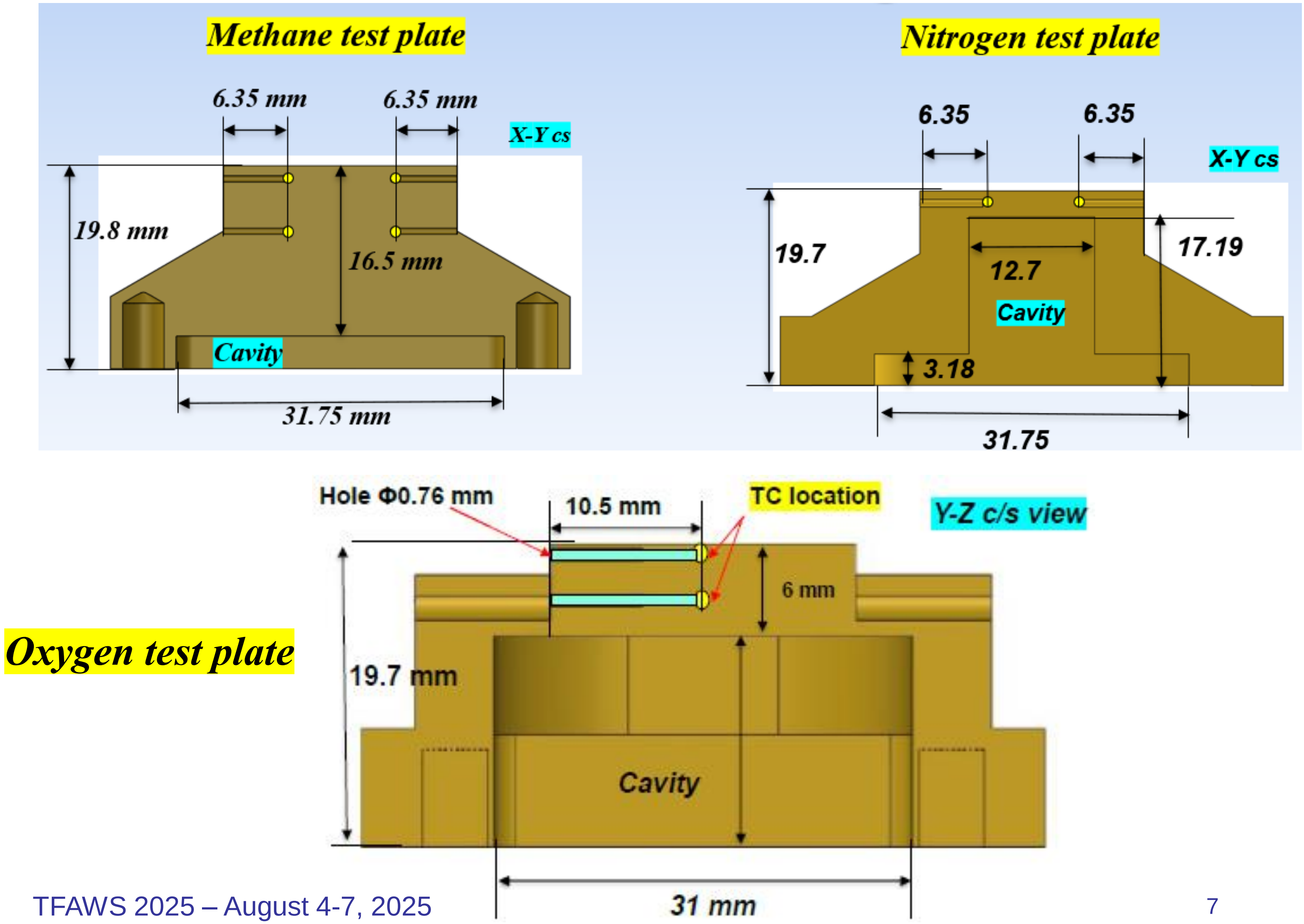
1. *UHP O_2 gas supply*
2. *Sonic nozzle*
3. *Gas precooler*
4. *Flow straightener*
5. *LN_2 bath connected to dewar*
6. *Brass test plate*
7. *Heater*
8. *Outlet mass flow meter*
9. *LED light source*
10. *Collimating lens*
11. *DSLR camera (45 Mpx)*
12. *Front visualization camera*

Film Condensation Experiment: Chamber and Test Plate

Visualization Chamber



Brass Test Plates



STAR-CCM+ Fluid Film Model with Phase Change

- STAR-CCM+ [4] models thin liquid films on solid surfaces using a fluid film solver that computes a sub-grid film thickness for every boundary cell (1D solver)
- Fluid film can grow or shrink based on the condensation or evaporation depending on the local conditions
- Bulk vapor phase does is not coupled to the fluid film through momentum equation
  - Bulk vapor does not “see” fluid film
  - However, a drag force term can be implemented so that pressure variations are accounted for in film shape

- **<u>Sub-Grid Solution Procedure:</u>**
  1. Calculate interfacial heat flux on each side of film interface assuming interfacial temperature is equivalent to T_{sat} (Eqn 1)
  2. Calculate mass transfer rate (Eqn 2)
  3. Calculate rate of change of film thickness (Eqn 3)

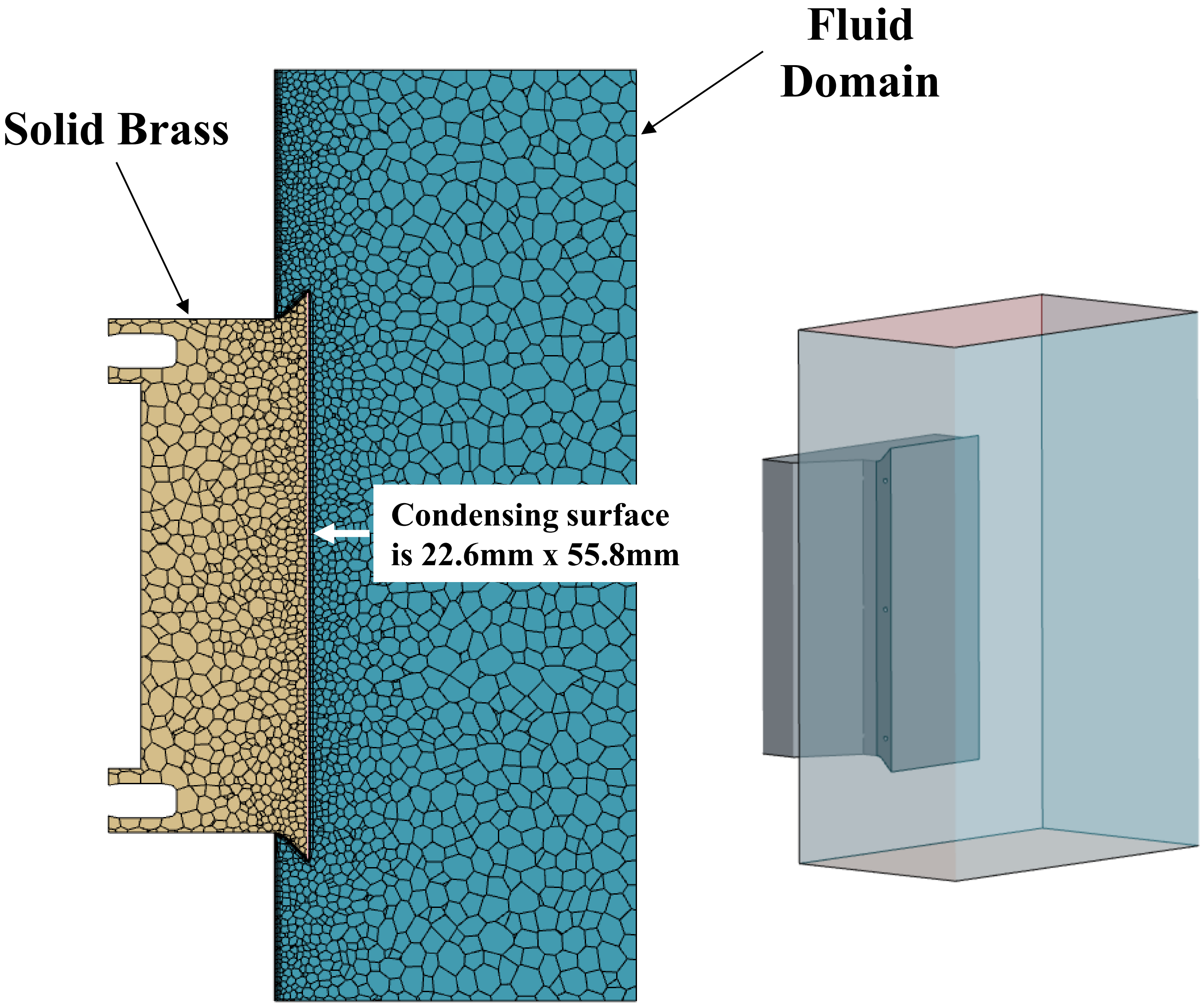
$$\dot{Q} = k\frac{dT}{dy} - k_f\frac{dT}{dy_f} \qquad \text{Eqn 1}$$

$$\dot{m} = \frac{\dot{Q}}{H^{vap}} \qquad \text{Eqn 2}$$

$$\dot{h} = -\frac{\dot{m}}{\rho_f} \qquad \text{Eqn 3}$$

CFD Model Setup

- 3D Conjugate Heat Transfer
  - Brass temperature-dependent properties
- Ideal Gas + Fluid Film Solver (Methane) with Condensation and Evaporation
  - Temperature-dependent vapor properties
  - Constant liquid film properties
- Laminar flow
- Unsteady Δt = 0.05s
- Run until steady state condition is achieved



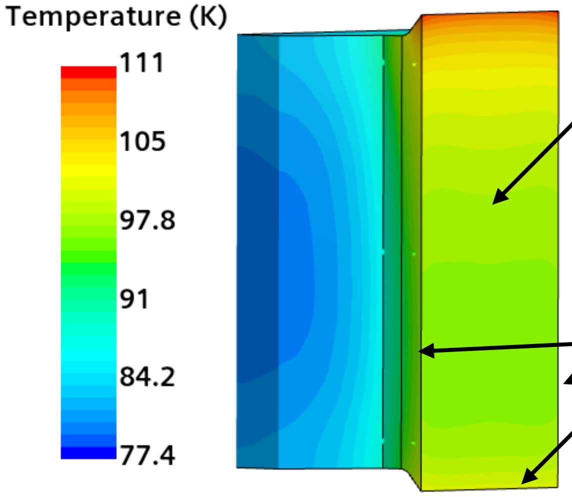
Condensing surface is 22.6mm x 55.8mm

Model Boundary Conditions

Test	Inlet vapor velocity, V_{vapor} (m/s)	Inlet vapor temperature, T_{vapor} (K)	Test plate temperatures (K)				Film thickness, t_{film} (μm)
			Near-surface		Internal		
120205	0.5	292.1	T_{s1}	108.0 ± 0.4	T_{i2}	104.4 ± 0.6	–
			T_{s2}	100.5 ± 0.3	T_{i2}	95.2 ± 0.4	20.1 ± 1.4
			T_{s3}	97.15 ± 0.2	T_{i3}	92.2 ± 0.2	–

$T_{i,fluid}$ = 292.1K

$T_{i,solid}$ = 115K (just above saturation temp)

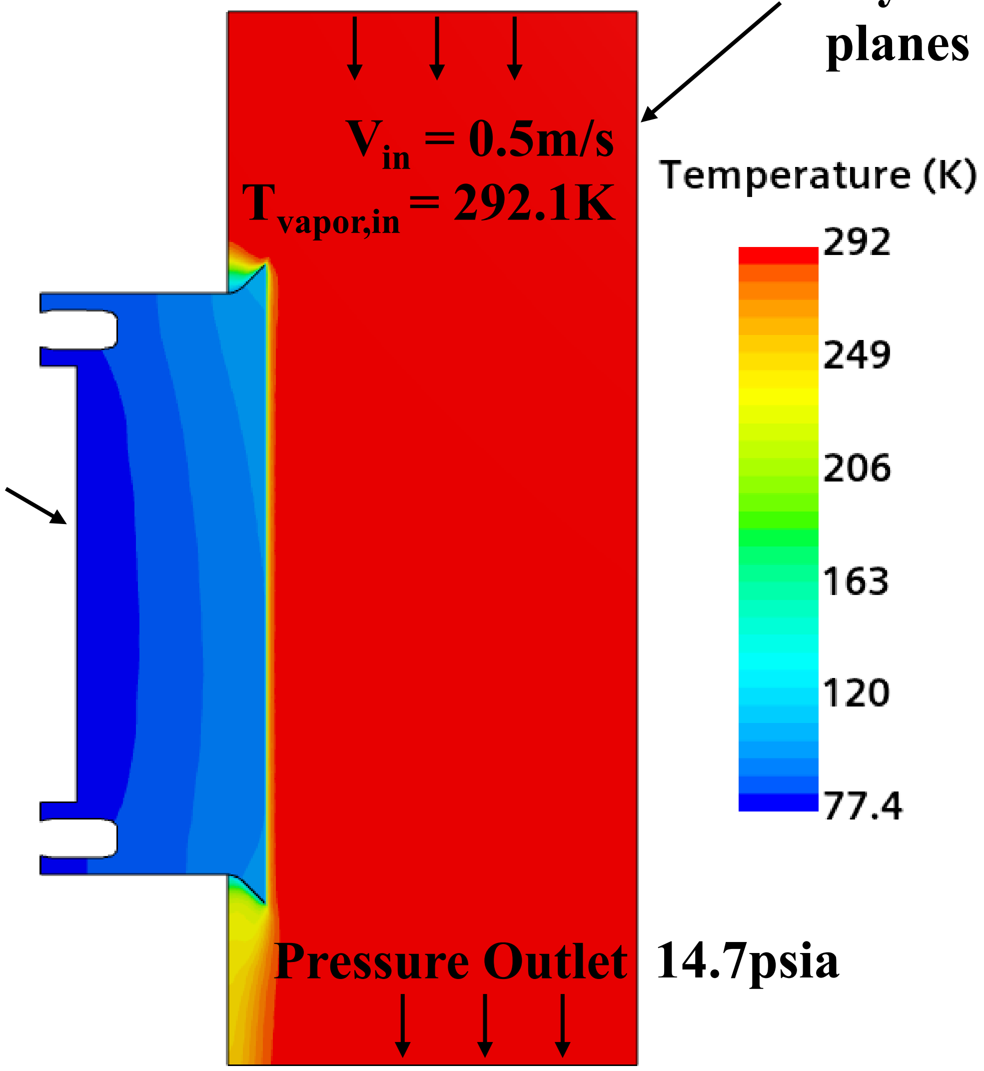


Solution Time 50 (s)

Condensing surface/film region

“Edge outlet” for film to flow off plate

T_{bath} = 77.4K



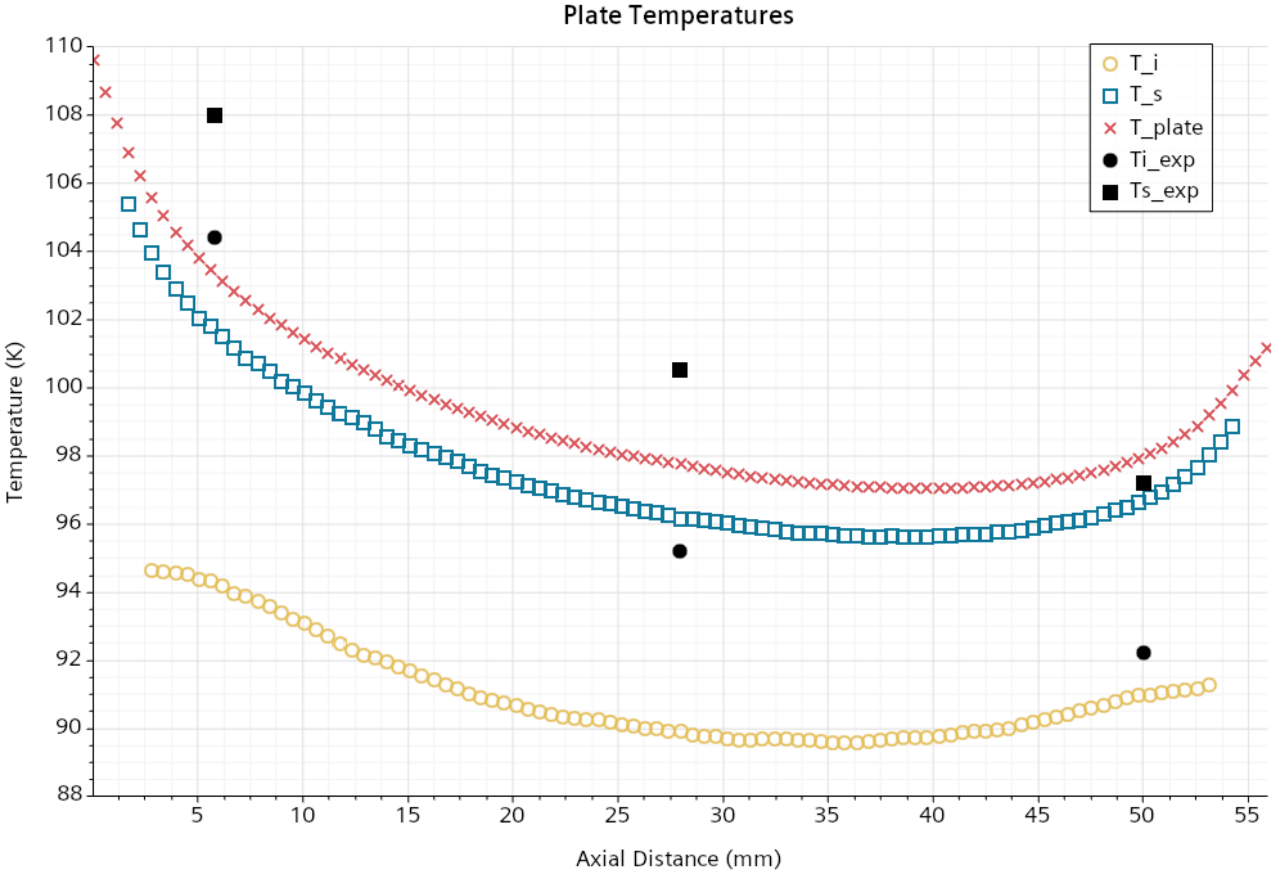
Sym planes

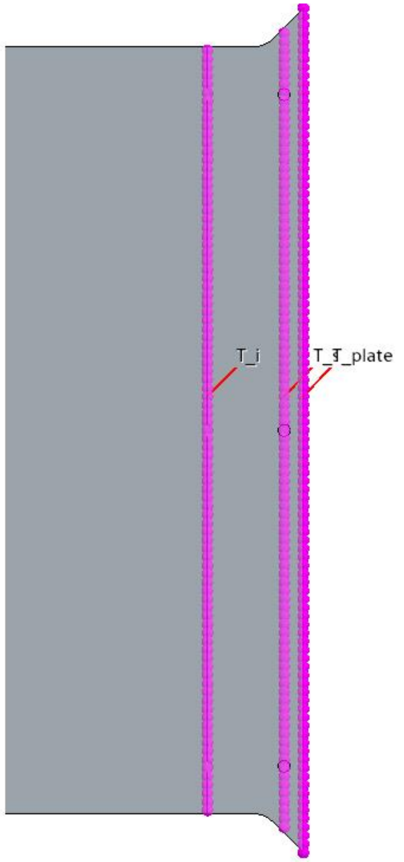
14.7psia

Solution Time 50 (s)

Preliminary CFD Results: Plate Temperatures

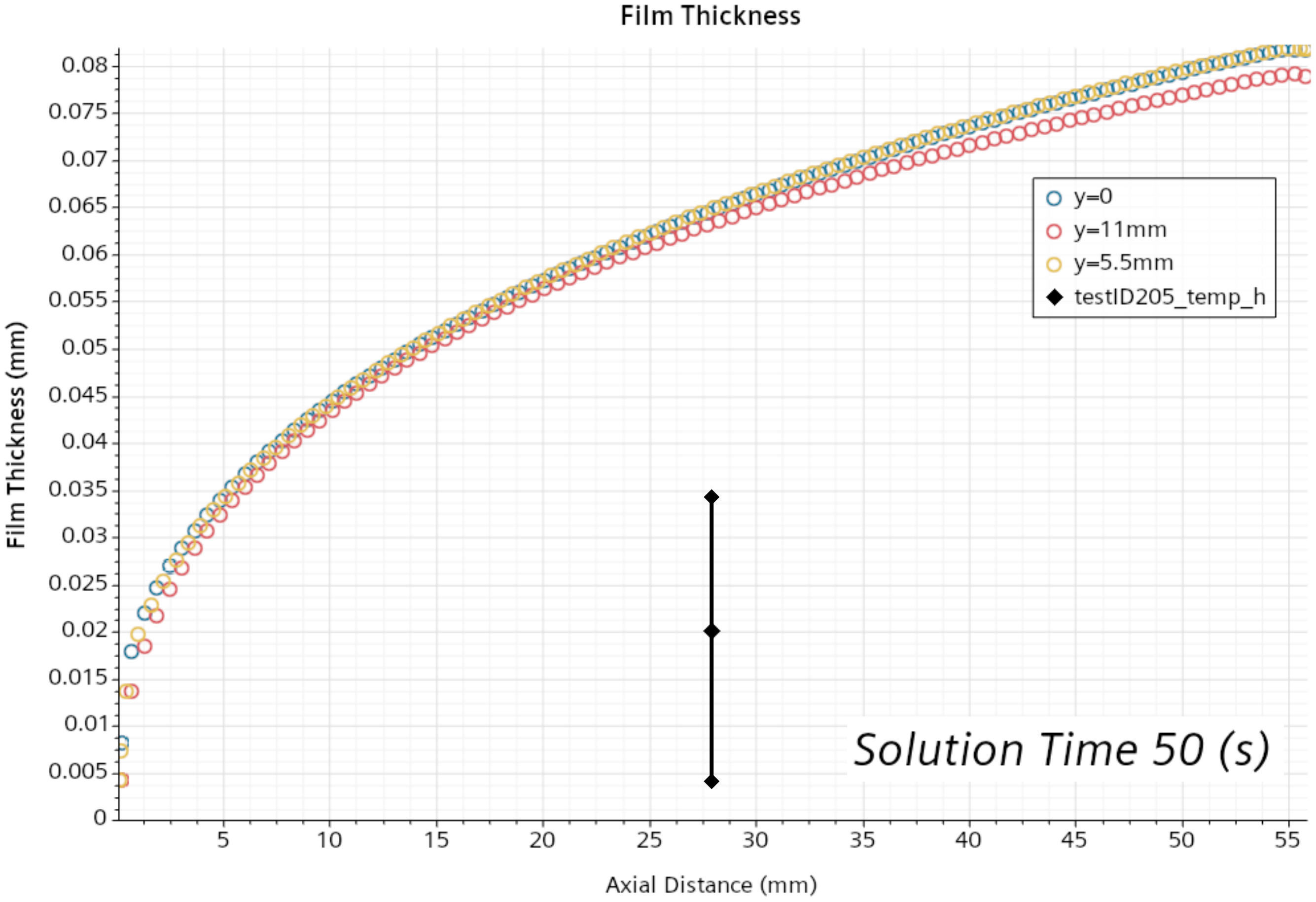
- Downstream temperatures match reasonably well
- Upstream and center temperature predictions are significantly under-predicted by 5-10K
- Constant wall temperature set to LN2 bath temperature likely not accurate due to stratification and heat leak

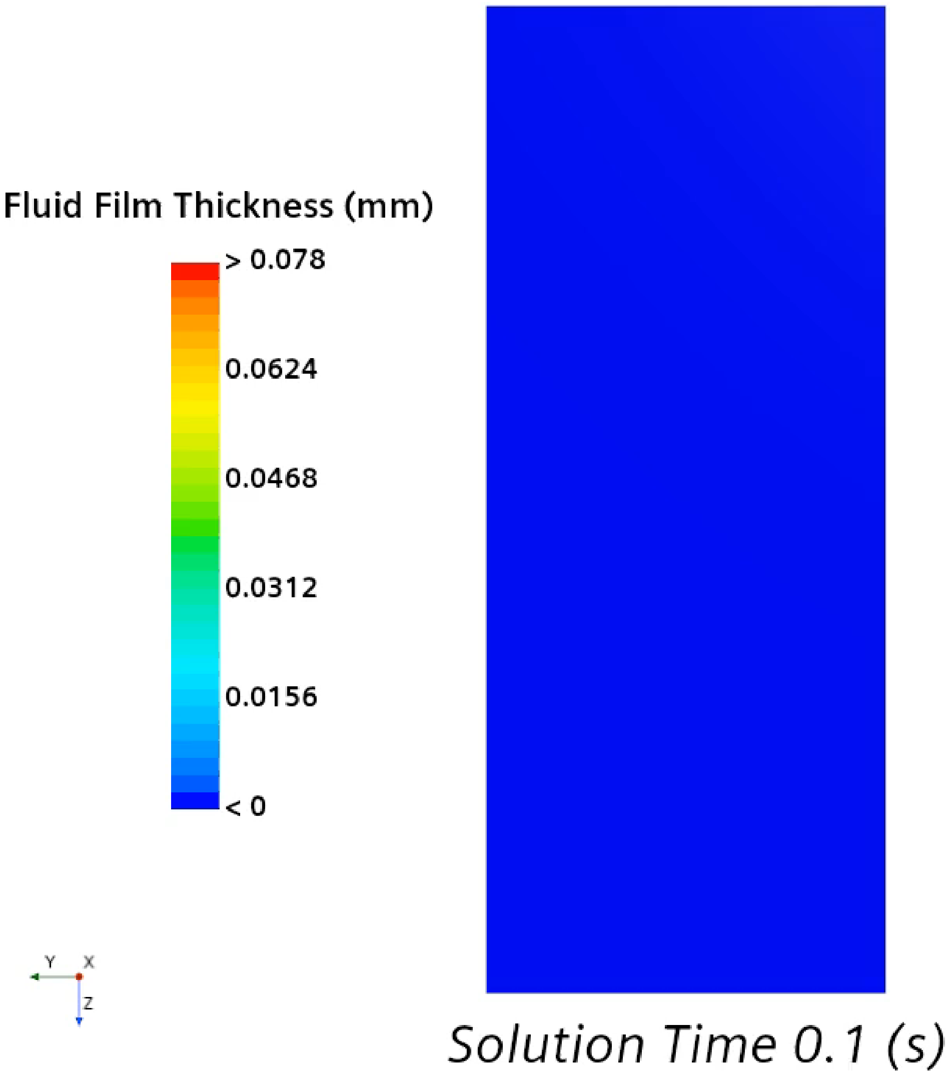




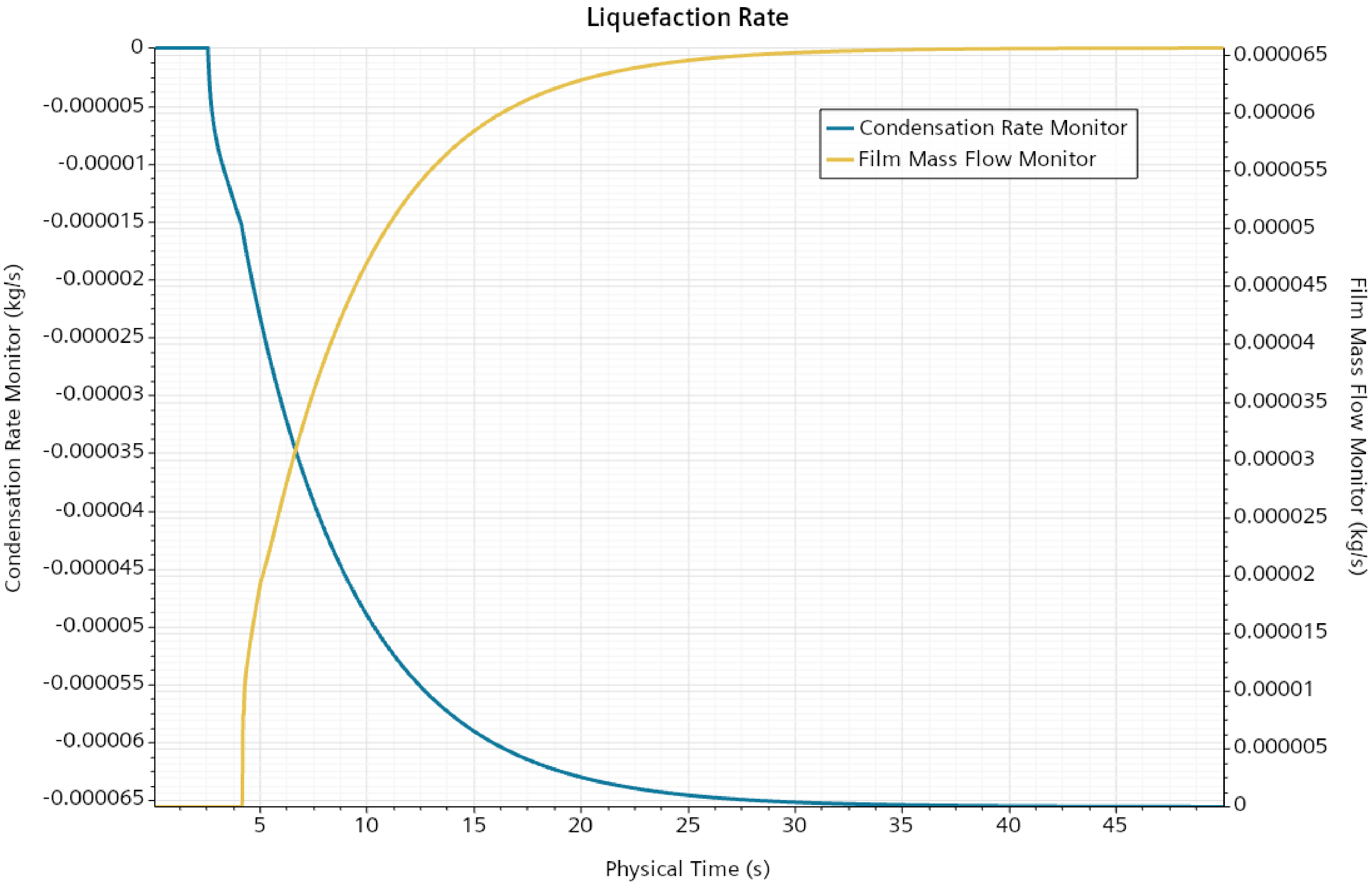
Preliminary CFD Results: Film Thickness

- Film thickness likely over-predicted due to under-prediction of solid temperatures

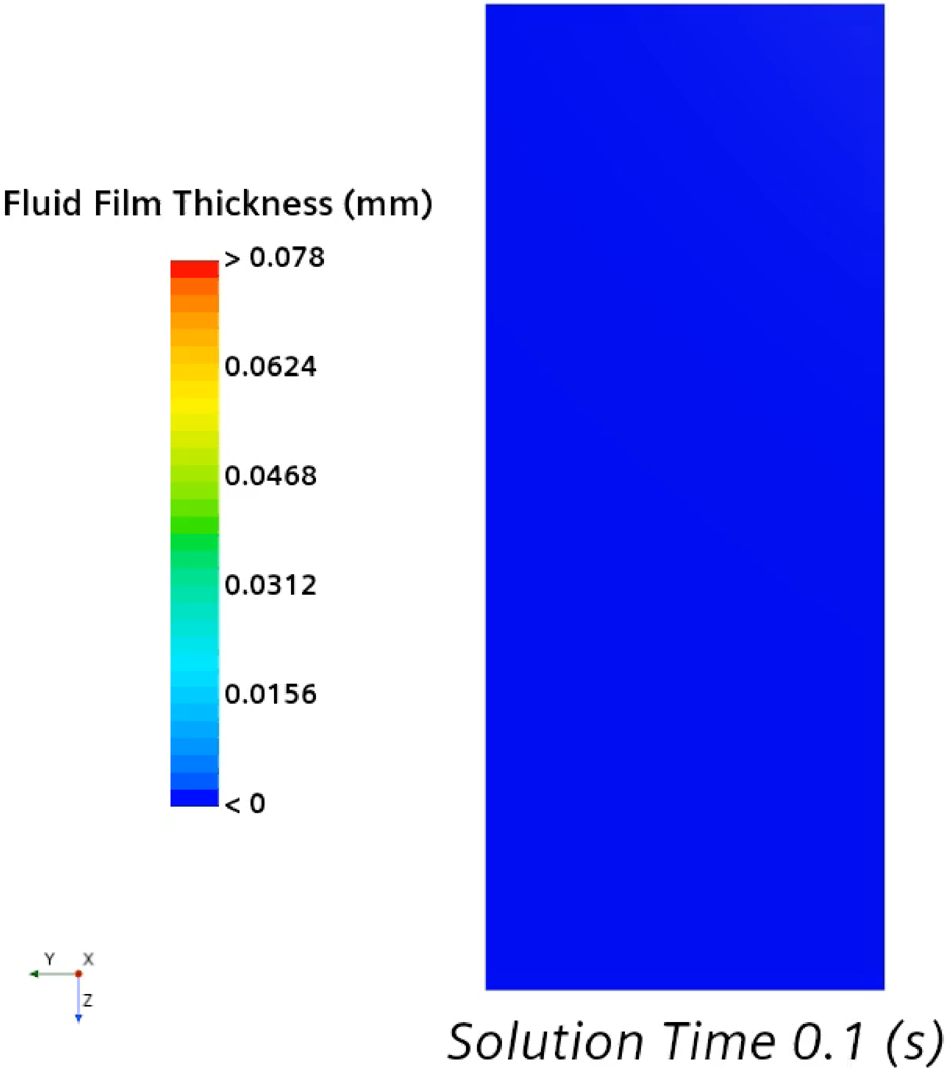


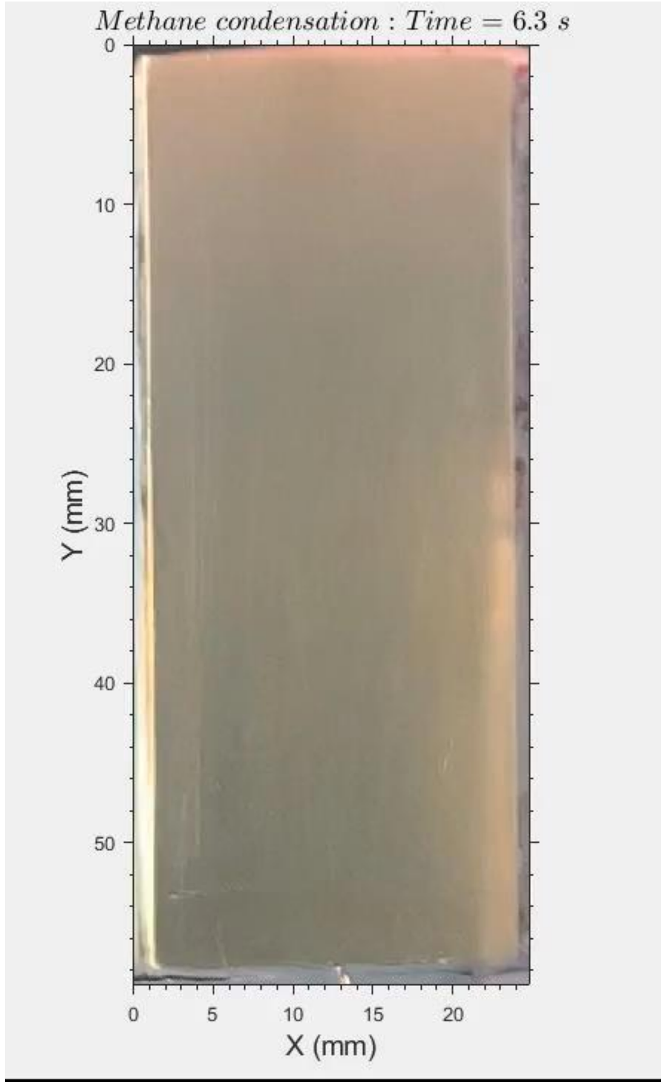


Preliminary CFD Results: Liquefaction Rate



CFD and Experiment





Discrepancy Investigations / Future Work

- Determine if over-prediction of film thickness is common between Methane, Nitrogen and Oxygen experiments
- Over-simplified LN2 bath temperature boundary condition and heat leaks (Thermal Desktop model of entire chamber)
- Brass temperature-dependent material properties
- Drag

References

1. https://science.nasa.gov/mission/viper/
2. https://www.nasa.gov/overview-in-situ-resource-utilization/
3. Johnson, W. L., Dimston, A. E., Valenzuela, J. G., Kashani, A., Smith, J. W., Chan, H. M., Wendell, J. C., Stephens, J. R., Balasubramaniam, R., Johnson, K. P., and Miller, E. J., “Liquefaction of Cryogenic Fluids for Production and Storage of Commodities on Extra-Terrestrial Surfaces,” Space Cryogenics Workshop, 2021.
4. Siemens Simcenter STAR-CCM+, Ver. 19.02.009-R8 (2402), Plano, TX, 2024.